

QUENCH PERFORMANCE AND QUENCH PROTECTION



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- **What is a Quench?**
- **Magnet Training and Quench Plateau**
- **Quench Origins**
- **Phenomenological Model of Training**
- **Quench Development**
- **The Effects of a Quench**
- **Hot Spot Temperature**

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Operating Conditions



- As explained elsewhere, for a given material, the boundary between the superconducting state and the normal resistive state can be represented by **a three-dimensional surface** which depends on operating temperature, applied magnetic flux density and transport current density.
- A magnet is normally operated at conditions corresponding to **a volume located beneath the critical surface**, where the entire coil is superconducting.

Critical Surface X-ing



- Starting from the operating conditions, let us **ramp up the current** supplied to a superconducting magnet, or let us assume that, somewhere in the magnet coil, there is an energy deposition which results in **a local temperature rise**.
- In ramping up the current (and thus, the magnetic field) or in raising the temperature, **we get closer to the critical surface**, and eventually, **we cross it**.

Quench Initiation (1/3)



- Crossing the critical surface means that, somewhere in the coil, a small volume of conductor switches to the normal resistive state.
- When switching to the normal resistive state, this small volume starts dissipating power by the Joule effect.

Quench Initiation (2/3)

- The dissipated power overheats the small volume, and, by thermal diffusion along the conductor (or by any other mechanism of heat transfer), the region surrounding the small volume.
- If the Joule heating is large enough (and if the cooling is not too strong), the surrounding region can, in turn, reach the transition temperature, switch to the normal resistive state, and start dissipating power.
- And so on.

Quench Initiation (3/3)



- Under certain conditions, a self-maintained process can be established —from transition, to power dissipation, to thermal diffusion and then again to transition— in which the normal zone (*i.e.*, the zone where the conductors have switched to the normal resistive state) grows irreversibly and propagates through the entire coil.
- This process is called a quench.

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Magnet Training (1/2)



- When cooling down and energizing a superconducting magnet for the first time, **the first quenches usually occur at currents below the limit expected from its conductor.**
- In most cases, however, it appears that, upon successive energizations, **the quench current gradually increases.**

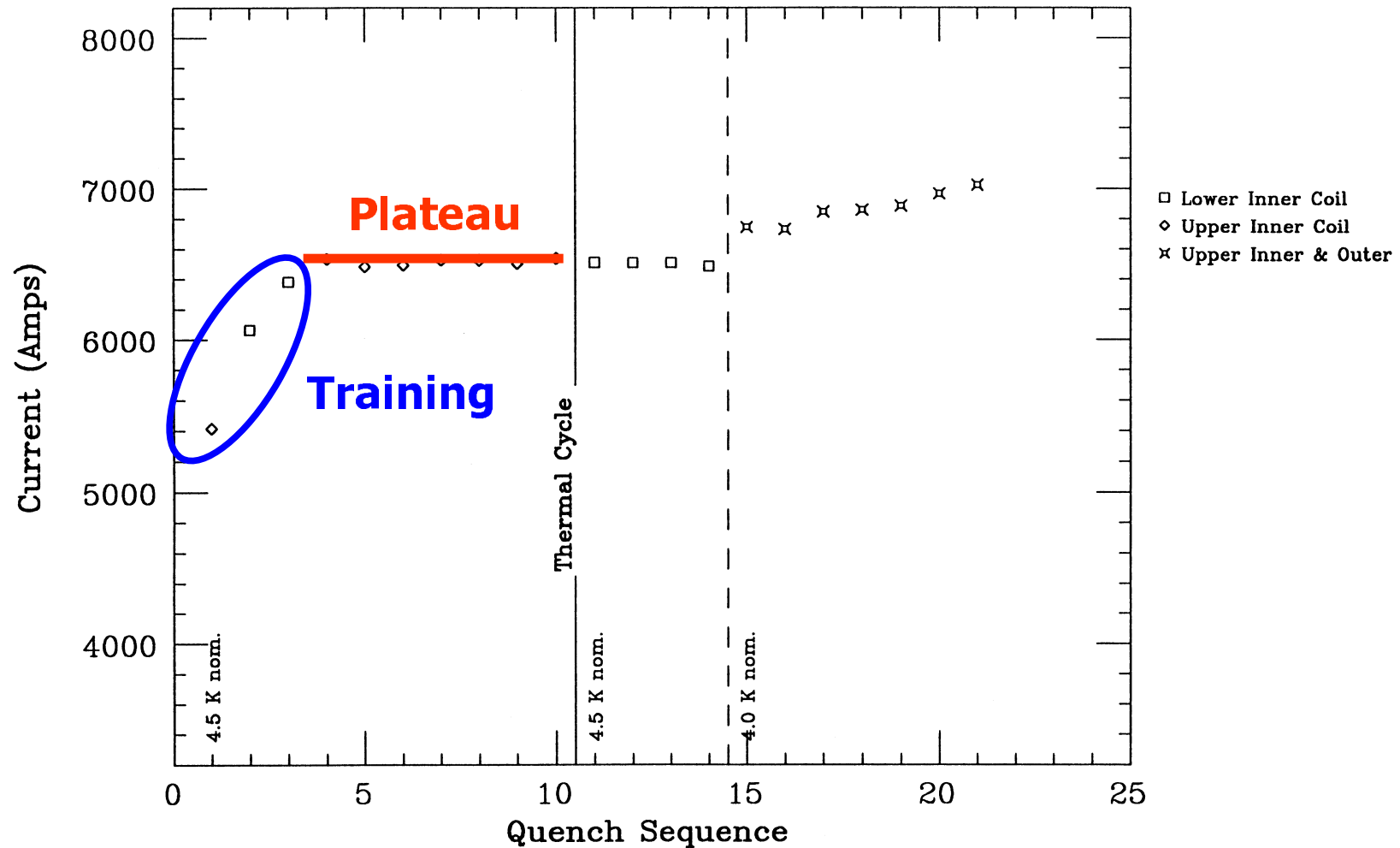
Magnet Training (2/2)



- This gradual improvement is called **magnet training**.
- The training often leads to **a stable plateau** corresponding more or less to the expected conductor limit at the given temperature.

Example of Training

SSC/BNL Dipole Magnet Model DSS010



Magnet Re-Training (1/2)



- Let us consider a magnet which, after a first cooldown, has been trained up to a stable plateau, and let us assume that this magnet has been warmed up to room temperature and cooled down again for a second energization test.

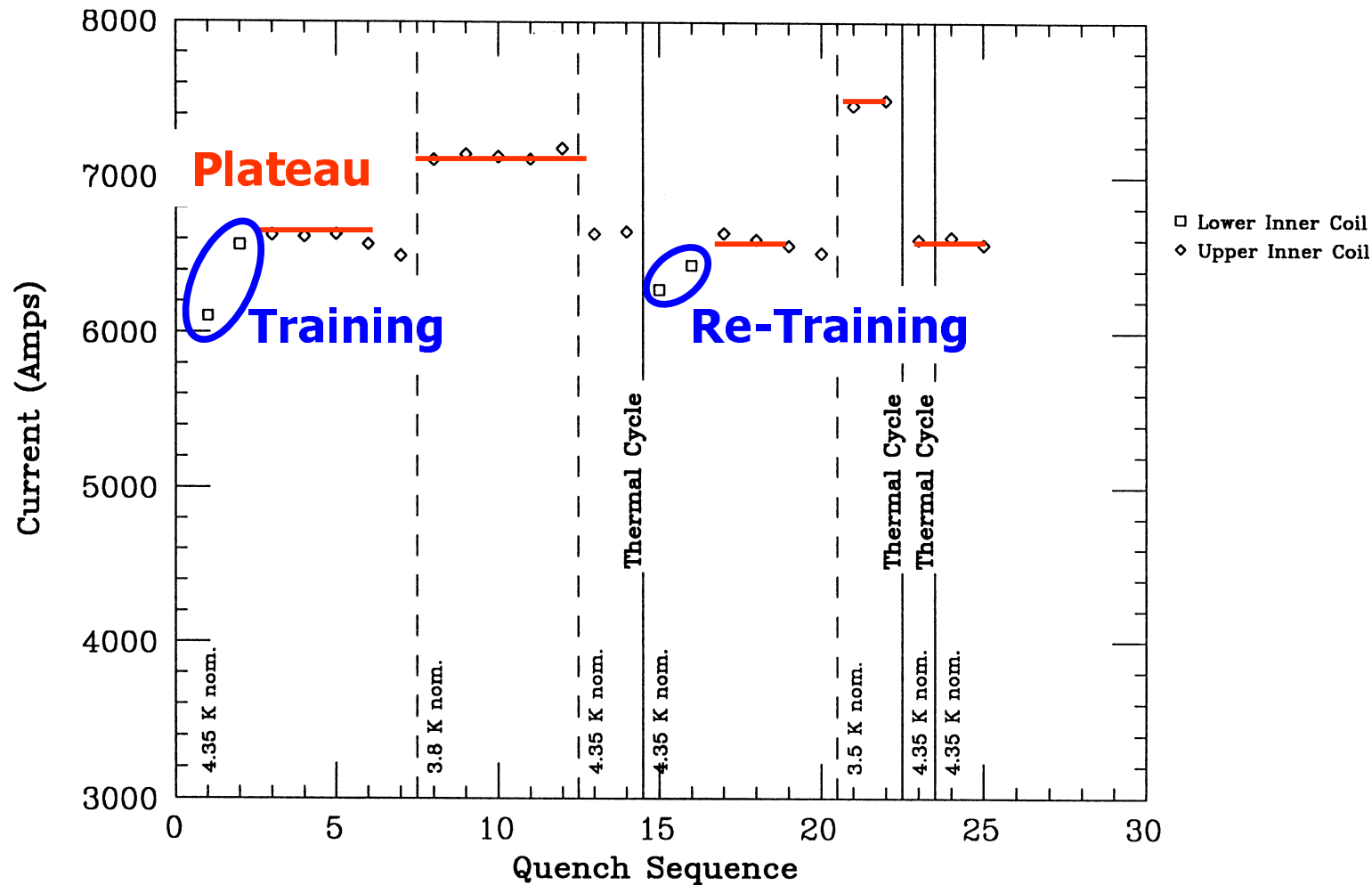
Magnet Re-Training (2/2)



- Upon the first energizations after the second cooldown, it can happen that the magnet goes back right away to the level of the plateau achieved during the first cold test.
- It can happen also that the magnet again requires a few training steps to restore its plateau.
- The latter behavior is called **re-training**.

Example of Re-Training

SSC/BNL Dipole Magnet Prototype DD017



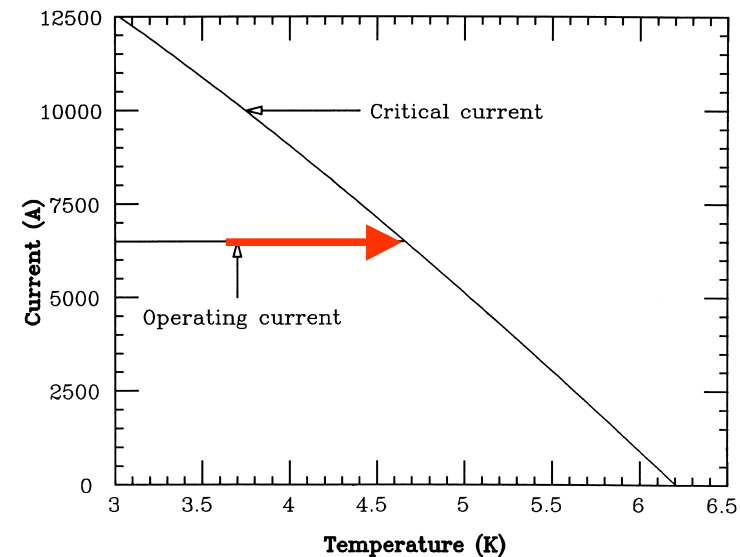
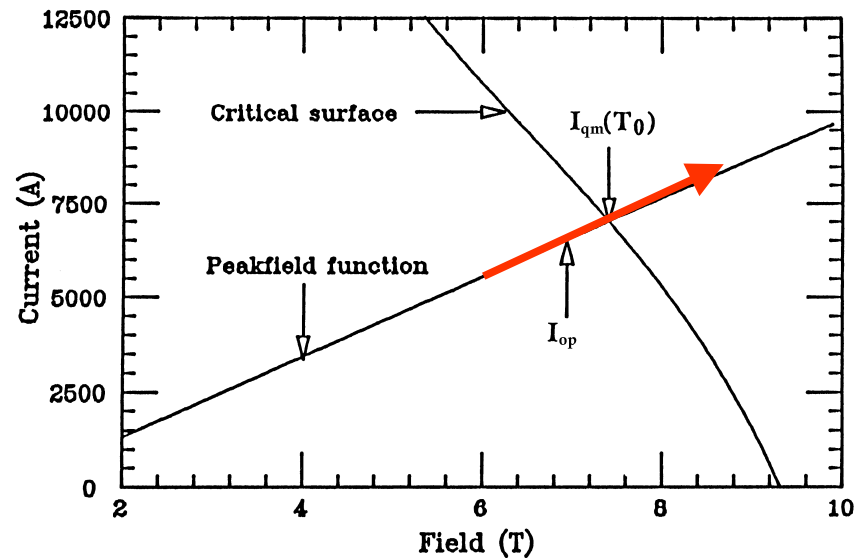
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Types of Critical Surface X-ing

- As we have seen, quenches originate because of a crossing of the superconductor critical surface somewhere in the magnet coil.
- This crossing occurs
 - either along the "peak field" line,
 - or along the temperature axis.



X-ing Along Peak Field Line (1/4)

- The maximum quench current of a magnet at a given temperature, I_{qm} , is estimated using a parametrization of the superconductor critical surface and assuming an average value of J_c at 4.2 K and 5 T over the magnet coil.
- The average J_c -value is usually determined from measurements on cable short samples.

X-ing Along Peak Field Line (2/4)

- Nevertheless, it can happen that the crossing of the critical surface along the peak field line occurs at an overall cable current that is below the expected I_{qm} .

X-ing Along Peak Field Line (3/4)



- Such quenches have at least two origins
 - a **local cable degradation**, which results in a local decrease of critical current and critical current density,
 - a large **current imbalance among cable strands**, which results in a strand carrying much more current than average and hitting the critical surface ahead of the others.

X-ing Along Peak Field Line (4/4)



- Quenches due to **a local cable degradation** are of the same nature as quenches occurring at the short-sample limit and can be identified as **conductor-limited quenches**.
- Quenches due to **large current imbalance** are more likely to occur at **high ramp rates**.

X-ing Along Temperature Axis (1/3)

- The temperature rises which initiate quenches result from **energy depositions** on the magnet coil.

X-ing Along Temperature Axis (2/3)

- The energy depositions that initiate quenches have at least three origins
 - (1) mechanical disturbances, such as stress relief or frictional motion under the Lorentz force,
 - (2) power dissipation from interstrand coupling currents,
 - (3) disruptions external to the magnet itself, such as synchrotron radiation or beam loss in accelerator magnets.

X-ing Along Temperature Axis (3/3)

- Quenches of the first origin are referred to as **mechanically-induced quenches** and reveal flaws in the mechanical design or in the assembly procedures which must be analyzed and corrected.
- **Coupling losses** are only of concern for **fast current cycles**.
- The effects of **external disruptions** can be reduced by implementing **intercepting screens or shields**.

Temperature Dependence of Conductor-Limited Quenches

- Conductor-limited quenches correspond to a crossing of the critical surface along the peak field line.
- When changing the operating temperature from T_0 to $(T_0 + \Delta T_0)$, the quench current should follow the superconductor critical surface and vary from $I_{qm}(T_0)$ to $I_{qm}(T_0 + \Delta T_0)$.
- Hence, the currents of conductor-limited quenches are expected to exhibit a strong correlation with temperature.

Temperature Dependence of Mechanically-Induced Quenches



- Conversely, the energy depositions resulting from mechanical disturbances should mainly depend on the Lorentz force level and should be relatively insensitive to small temperature variations.
- Hence, the currents of mechanically-induced quenches are not expected to be strongly related to magnet temperature.

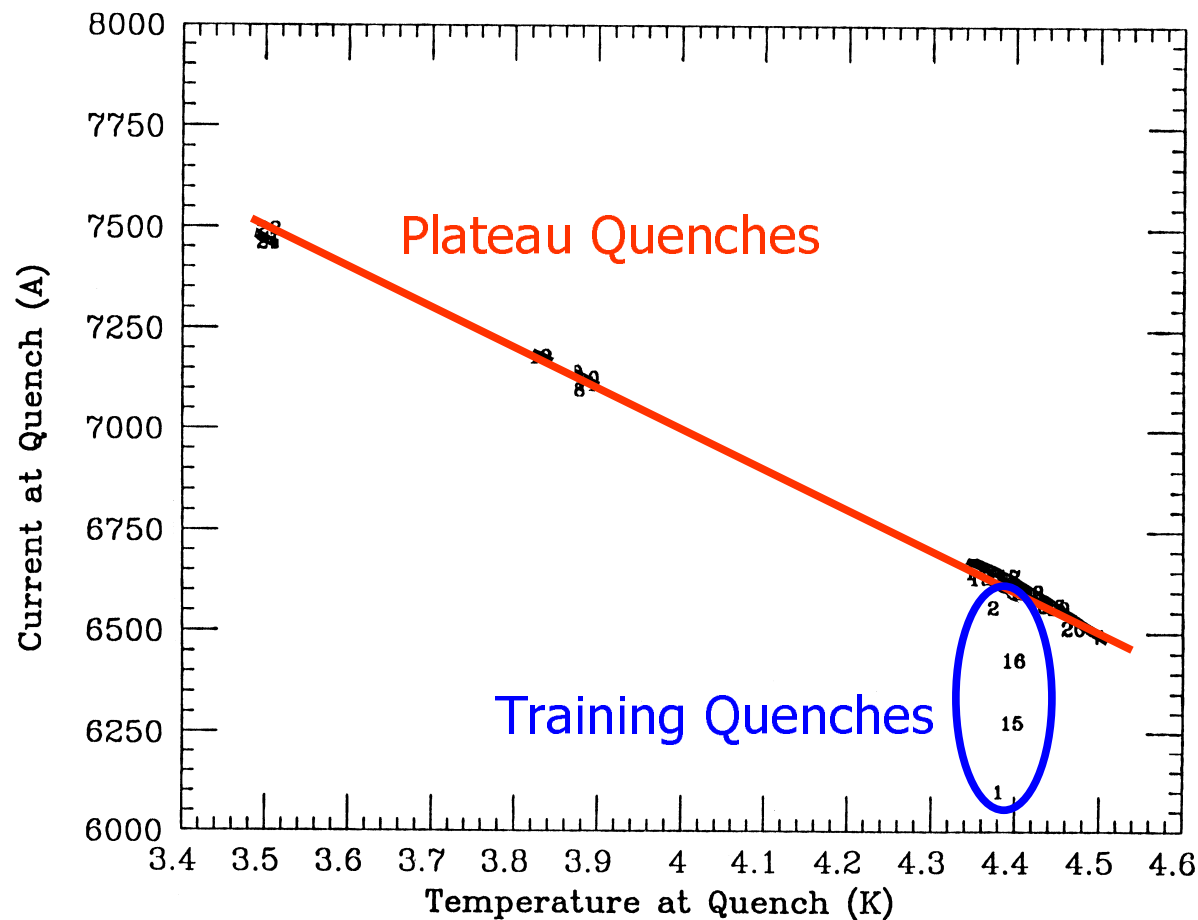
Discrimination Method (1/2)



- A practical method for discriminating between conductor-limited quenches and mechanically-induced quenches is **to vary the operating temperature of the magnet slightly** —for example, to increase it and then decrease it by 50 mK— and **to see if the quench current follows the change or not.**

Discrimination Method (2/2)

SSC/BNL Dipole Magnet Prototype DD0017



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Phenomenological Model of Training (1/5)

- Among the various quench origins considered above, only **mechanical disturbances** are likely to be affected by successive ramps to quench and lead to the kind of improvement in magnet performance referred to as training.
- A phenomenological explanation of magnet training is as follows.

Phenomenological Model of Training (2/5)

- When energizing a magnet, strong Lorentz forces are applied to the conductor strands which are transmitted to the coil support system through the insulation.
- In a geometry as complex as that of a magnet coil assembly, there are many interfaces where the Lorentz forces have tangential components, which are counteracted by friction.

Phenomenological Model of Training (3/5)

- As the current is ramped up and the Lorentz forces increase, it can happen that, somewhere in the coil, a static-friction coefficient is exceeded.
- Sliding then occurs, which results in heat dissipation and a local temperature rise.
- If the local temperature rise is large enough, a quench is initiated.

Phenomenological Model of Training (4/5)

- In the case of a quench caused by a so-called **stick-slip motion** in the magnet assembly, the motion responsible for the quench and/or the thermal stresses developed in the magnet coil during the quench can **improve the mechanical stability of the troubled interface**.
- As a result, upon subsequent energizations, the Lorentz forces are better supported in the previously troubled area and **the same current level can be achieved without exceeding the local static friction coefficient**.

Phenomenological Model of Training (5/5)


- Then, the current can be further ramped up until, somewhere else in the coil, another static friction coefficient is exceeded, which, in turn, provokes a frictional motion large enough to initiate a quench — and so on.
- Quench after quench, the current can be ramped up to higher levels, until it reaches the cable current limit.
- Of course, if the mechanical flaws at the origins of the disturbances are too large, the magnet cannot be trained and keeps quenching erratically.

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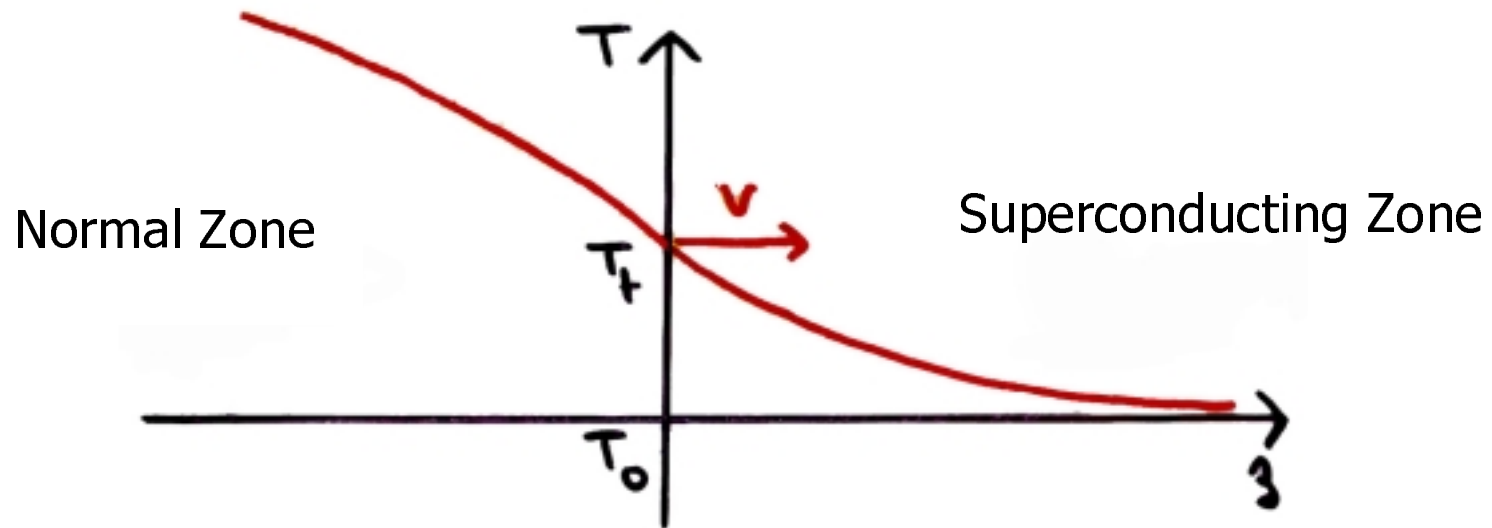
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Quench Propagation Velocity (1/3)



- One of the most remarkable features of a quench is that, once it has been initiated, **the normal zone propagates along the conductor at a constant velocity.**
- This velocity is called the *quench propagation velocity.*

Quench Propagation Velocity (2/3)



- In a simple adiabatic model, the quench propagation velocity, v , can be estimated by writing that, at the boundary between normal and superconducting zones, a fraction of the power Joule, P_J , dissipated in the normal zone is diffused by heat conduction along the conductor and heats up v meters per second of superconducting zone from T_0 (initial temperature) to T_t (transition temperature).

Quench Propagation Velocity (3/3)

- Hence, we have

$$\frac{D_{\text{th}}}{v} P_J \approx v \Delta H_0$$

where D_{th} is the thermal diffusivity along the conductor (m^2/s), and ΔH_0 is the conductor enthalpy between T_0 and T_t (J/m^3).

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Quench During Operation



- Although a lot of efforts are devoted to the conception and fabrication of stable magnets, **quenches do occur during superconducting magnet operations.**
- The quenches must be handled in order **to avoid any damage** of the quenching magnet, **to ensure the safety** of the installation, and **to minimize system down time.**

The effects of a Quench (1/2)



- As described elsewhere, once a small volume of conductor has switched to the normal resistive state, it dissipates power by the Joule effect.
- A fraction of this dissipated power is transferred to the surroundings of the initial volume of transition (either along the conductor, or, transversely, to the conductor insulation or the helium), but the main part is consumed locally in overheating the conductor.

The effects of a Quench (2/2)



- In a very short time (a few tenths of a second in the case of accelerator magnets), the conductor temperature, initially that of the helium, reaches room temperature, and, if the magnet is not discharged, keeps on increasing.

Temperature Rise



- The temperature rise consecutive to a quench must be limited for at least three reasons
 - to restrict the thermal stresses induced in the quenching coil,
 - to prevent superconductor degradation,
 - to avoid insulation damage.

Thermal Stresses



- Thermal stresses result from thermal expansion differentials between coil components.
- For most materials, thermal expansion starts to be significant for temperatures **above 100 K.**

Superconductor Degradation

- The critical current density of NbTi is affected by exposure at temperatures **above 250 °C**.
- The degradation amplitude depends on the temperature and on the duration of the exposure: at 250 °C, it takes ~1 hour to get a significant degradation, while it can take less than a minute at 400–450 °C.
- This degradation results from **a growth of the β -phase grains** in the NbTi alloy microstructure, **which affects the distribution of α -Ti precipitates and alters pinning**. (The α -Ti precipitates get dissolved for temperatures above 600 °C).

Insulation Damage



- The polyimide materials commonly used to insulate NbTi cables lose most of their mechanical properties for temperatures **above 500 °C**.

Maximum Temperature Specification

- An upper limit for conductor heating consecutively to a quench is 400 °C.
- Most magnets are designed not to exceed 300 to 400 K, and whenever possible, the limit is set to 100 K.

Protecting a Quenching Magnet

- The source of conductor heating in a quenching magnet is **power dissipation by the Joule effect**.
- Power keeps being dissipated as long as there is current in the magnet coil.
- Hence, to eliminate the heat source and limit temperature rise, it is necessary **to ramp down the magnet current**.

On the Use of Quench Protection Heaters (1/2)

- To discharge a quenching magnet, all its **stored magnetic energy must be converted into resistive power.**
- If the quench propagates very slowly, and if the zone where the conductor has switched to the normal state remains confined to a small volume, there is a risk that **a large fraction of the stored energy be dissipated in this small volume.**

On the Use of Quench Protection Heaters (2/2)

- To prevent burnout, it is desirable to maximize the volume in which the energy is dissipated by ensuring that the **normal resistive zone spreads rapidly throughout the quenching coil.**
- If needed, this can be done by means of heaters, implemented near the magnet coils and fired as soon as a quench is detected.
- These heaters are referred to as **quench protection heaters.**

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Hot Spot



- The volume of conductor that heats up the most significantly during a quench is the spot where the quench first originated.
- It is called the hot spot.

Hot Spot Temperature (1/4)



- An upper limit of the hot spot temperature, T_{\max} , can be determined by assuming that, near the hot spot, all the power dissipated by the Joule effect is used to heat up the conductor.

Hot Spot Temperature (2/4)

- Then, near the hot spot, the heat balance equation reduces to

$$C(T) \frac{dT}{dt} = \rho(T) \left[\frac{I(t)}{S} \right]^2$$

where C is the specific heat per unit volume of conductor, ρ is the conductor resistivity in the normal state, S is the conductor cross-sectional area and $I(t)$ is the current at time t .

Hot Spot Temperature (3/4)

- The previous equation can be rewritten

$$\frac{C(T)}{\rho(T)} dT = \left[\frac{I(t)}{S} \right]^2 dt$$

where the left member only depends on temperature and on cable properties, and the right member only depends on time and on current decay characteristics.

Hot Spot Temperature (4/4)

- By integration over the duration of a quench, we get

$$\int_{T_0}^{T_{\max}} \frac{C(T)}{\rho(T)} dT = \int_{t_0}^{+\infty} \left[\frac{I(t)}{S} \right]^2 dt$$

where t_0 is the time of quench start, and T_0 is the coil temperature at t_0 .

MIIT Integral

- The **MIIT** (Mega I times I versus Time) integral is defined as

$$\text{MIIT} = \frac{1}{10^6} \int_{t_0}^{+\infty} \left[\frac{I(t)}{S} \right]^2 dt$$

- The MIIT integral is easy to compute from data recorded during a quench and can be used to determine the hot spot temperature.

Example of Hot Spot Temperature Estimation

